An Investigation of Terrain-Atmosphere-Ocean Interactions Along the Coastal Regions of North America

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LONG-TERM GOALS

The long-term goal of this project is to improve our understanding of: (1) the structure, evolution, and dynamics of the interaction of extratropical fronts/cyclones with the coastal orography of the western U.S., (2) air-sea interactions associated with coastal fronts and rapidly deepening cyclones along the East Coast, and (3) the ability of mesoscale models to simulate coastal phenomena at high resolution.

OBJECTIVES

During the past year one objective has been to complete a detailed modeling study of a landfalling frontal case observed during the COAST field project on 1 December 1995. This study expands on observational results presented in Yu and Smull (2000), in which they hypothesized that the flow blocking associated with the steep coastal terrain of northern California led to the rapid intensification of a narrow cold frontal rain band near the coast, and the subsequent weakening of this precipitation band to the south was the result of decreased flow blocking adjacent to the lower terrain. Yu and Smull (2000) did not have sufficient observations to quantify the role of terrain versus diabatic and larger-scale atmospheric forcings. My project uses the MM5 at high resolution to investigate the three-dimensional evolution and mechanisms for rapid intensification and subsequent decay of the front moving southward along the coast.

The PI participited in the PACJET field program in Febraury of 2001 along the California in order to obtain more data of landfalling fronts using the NOAA P-3 aircraft. Also, in order to better understand the range of sensitivity of the terrain-frontal interactions as a function of the large-scale flow pattern, low-level stability and windspeed, this project will complete a set of idealized three-dimensional MM5 simulations of landfalling synoptic systems. The objective this past year has been to develop methods to initialize the idealized MM5 runs.

The final goal of this past year has been to complete a comprehensive verification of the MM5 and Eta models along the U.S. East coast. There have been no long-term verification studies of high resolution mesoscale models in this region, a place where air-sea and land-water interactions are important in the evolution of nor-easters, coastal fronts, and sea breezes. This study is quantifying the strengths and weaknesses of increasing resolution in a coastal region where there is fairly limited terrain.

APPROACH

This investigation has employed the Penn State/National Center for Atmospheric Research (PSU-

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14. ABSTRACT
The long-term goal of this project is to improve our understanding of: (1) the structure, evolution, and dynamics of the interaction of extratropical fronts/cyclones with the coastal orography of the western U.S., (2) air-sea interactions associated with coastal fronts and rapidly deepening cyclones along the East Coast, and (3) the ability of mesoscale models to simulate coastal phenomena at high resolution.

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NCAR) mesoscale model (MM5) in order to investigate the physical processes of frontal modification along the coastal zones of North America. The COAST field study event of 1 December 1995 was simulated down to 3 km resolution over coastal northern California. The model was compared with high resolution obsevations from the NOAA P-3 aircraft and coastal wind profilers. After a sucessful control simulation was obtained, sensitivity simulations were completed in which either the coastal terrain was removed or diabatic effects from precipitation were turned off. For all simulations the simulated frontogenesis forcings were evaluated to quantify the reasons for the rapid changes in frontal temperature gradients over the coastal zone.

Other potential case studies are available from the PACJET (Pacific Landfalling Jets) field experiment, which occurred along the California coast in February 2001. The PI has begun diagnosis of the 9 February 2001 event, in which the front interacted with Cape Mendocino along the California coast. Diagnosis of the NOAA P-3 tail radar and high resolution simulations will allow docomentation of a front interacting with with a large bend in coastal terrain.

Since mesoscale models have been shown to be successful in realtically simulating the interaction of fronts with topography, they can also be used to conduct a full suite of idealized simulations. For these idealized simulations we specify the strength and orientation of the front or cyclone hitting the coast as well as the background stability and flow. This systematic approach will allow us to expand on current frontal-terrain theory, which has simply focussed on the amount of low-level flow blocking.

A real-time MM5 modeling system has been set up in order to determine benefits/problems of high resolution model forecasts along the East Coast. A 36-km horizontal resolution domain covers the eastern two-thirds of the United States and western Atlantic, a 12-km resolution nested grid extends across the Northeastern U.S., and an inner 4-km resolution grid encompasses Long Island and surrounding areas. The MM5 forecasts are compared with all available observations and the NCEP Eta model in order to assess model skill versus resolution across coastal New England.

WORK COMPLETED

A landfalling frontal case (COAST IOP8) along the California coast (1 December 1995) has been successfully simulated and diagnosed using the MM5 down to 3-km resolution. The 12-h NCEP analyses (2.5^{o} resolution), enhanced with additional surface and upper-air observations, were used for initial and lateral boundary conditions for the outer 27-km resolution domain. The control (CTL) simulation has been verified against conventional observations as well as aircraft and profiler observations shown in Yu and Smull (2000). During the past year the MM5 simulations were used to better understand the three-dimensional evolution and physical mechanisms. Evaluating the physical mechanisms was done by writing software to diagnose the large-scale atmospheric forcings as well as the total fronotogenesis, which includes diabatic heating output from the model. Additional 3-km simulations were completed in which the coastal terrain was removed and/or latent heating/cooling processes in the model were turned off. These diagnostics and experiments allow us to separate the role of terrain versus large-scale or diabatic processes. The results have been written up for publication.

A technique has been implemented to generate idealized initial and boundary conditions for the MM5 in order to investigate landfalling synoptic systems over a number of different situations. The technique allows for the specification of baroclinic disturbances that feature vertical variations of the height, temperature, and wind fields in terms of phase lag, wavelength, and phase speed. The MM5 simulations can either use actual terrain or a large elliptical mountain. All idealized runs are nested down to 5 km resolution, and the real terrain runs are centered around the northern California coast.

For the East Coast the MM5 has been set up to run in real-time twice daily down to 4-km resolution around Long Island (http://atmos.msrc.sunysb.edu/html/alt_mm5.cgi). Initial and lateral boundary conditions for the MM5 are generated by interpolation of the National Centers for Environmental Prediction (NCEP) "early-ETA" 32-km initial analysis (221 grid) and 80-km resolution forecast fields (104 grids). During the past several months the real-time system has been upgraded from version 2 to version 3 of the MM5. This allows for soil moisture initialization using the Eta as well direct prediction of the 10-m wind and 2-m temperature. The MM5 and Eta forecasts for the past two years have been verified using all available observations to assess model skill versus resolution across coastal New England. Spatial maps of model biases and errors have been created in the coastal zone. These results are currently being written up for publication.

RESULTS

Our investigation has identified mechanisms that led to the observed rapid evolution of a landfalling weak cold front along the steep mountainous northern California coast on 1 December 1995. The landfalling surface baroclinic trough did not possess strong frontal characteristics a few hundred kilometers upstream of the coast (not shown). As this trough approached to within 100 km of the coast, it developed more baroclinic character—including a sharp low-level windshift from southerly to westerly flow, a 1-2 ^{o}C /100 km temperature drop, and an intense narrow cold frontal rainband (NCFR) by 0700 UTC 1 December 1995 (Fig. 1a). Vertical cross sections illustrate that the front had a 30-40 km tipped-forward frontal structure between the surface and 800 mb (not shown). The leading edge of the baroclinicity was associated with the prefrontal precipitation band at this time.

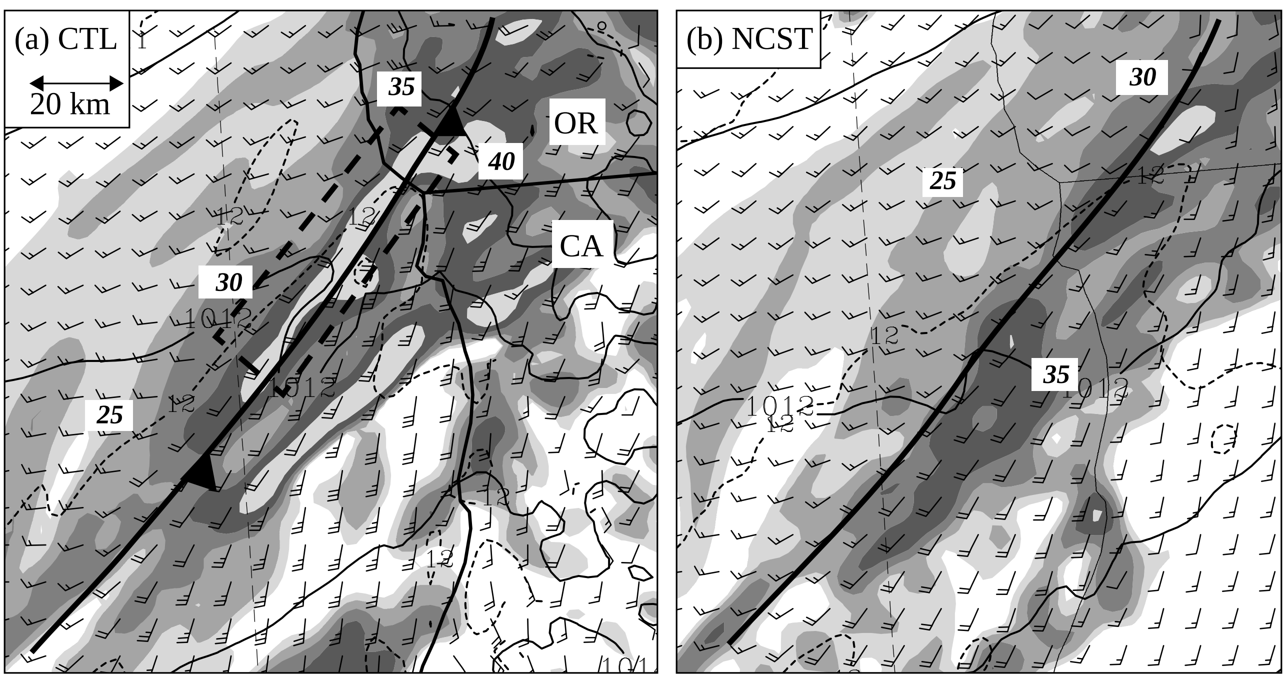

Figure 1: (a) Model surface analysis for a portion of the 3-km domain at 0700 UTC 1 December (19 h) showing sea-level pressure (solid) every 1 mb, winds 30 m above surface (1 full barb = 10 kts), 500-m temperatures (dashed) every 1 ^{o}C, and model reflectivities (shaded every 5 dBZ). The dashed box represents the area where the average frontogenesis forcings are calculated in Fig. 2. (b) Same as (a) except for the no coastal terrain (NCST) run. [The frontal precipitation band, windshift, and temperature gradient near the California coast intensified more rapidly in the CTL than the simulation without coastal terrain (NCST).]

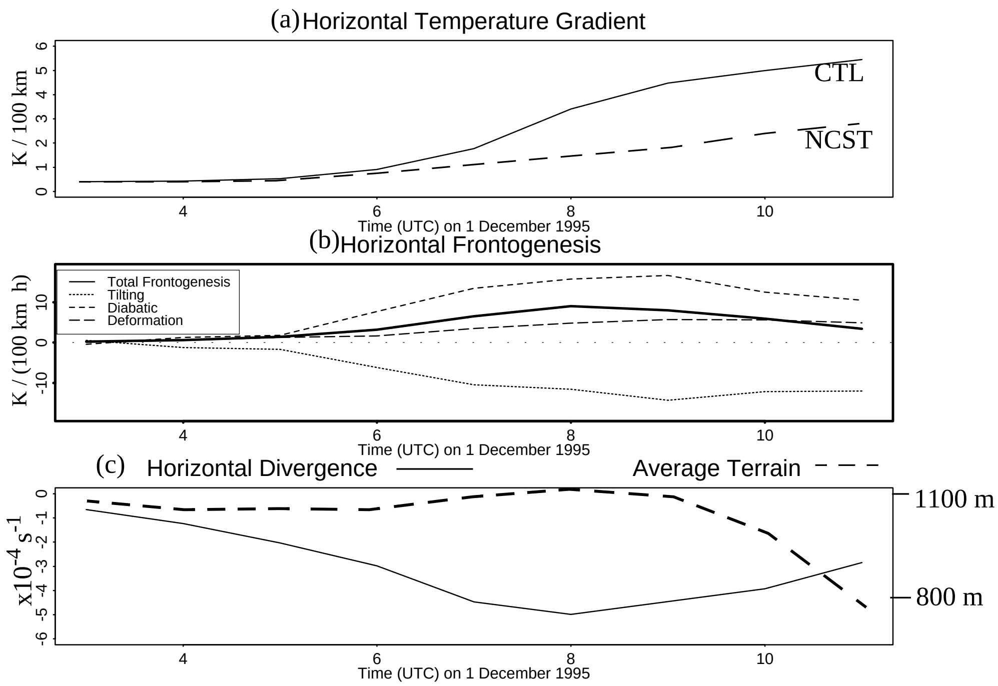

Figure 2. Time series traces from 0300 to 2300 UTC 1 December 1995 at 0.5 km MSL for the box shown on Fig. 1a showing the (a) CTL and NCST potential temperature gradient (K/100 km), (b) CTL frontogenesis terms (K/(100 km h), see inset for terms), (c) CTL horizontal divergence (10^{-4} s^{-1}) and the average terrain (m) within 200 km of the coast. [There is a rapid increase in frontal temperature gradients adjacent to the steep coastal topography. Half of this increase is caused by deformation frontogenesis and the other half by differential diabatics across the front.]

The large-scale atmospheric forcings were also diagnosed using the MM5. The quasi-geostrophic vertical velocity calculated from the MM5 for the 700-500 mb layer increased in intensity over the eastern Pacific as the upper-level trough approached the coast (not shown), which suggests that the large-scale forcing was generally favorable for the rapid development of precipitation in the coastal zone, albeit on much greater spatial/temporal scales. This was further confirmed by the NCST run, which showed a rapid development of widespread light to moderate coastal precipitation even in the absence of terrain effects (Fig. 1b). The NCST simulation also illustrates that the coastal terrain is necessary to intensify the front to that observed by Yu and Smull (2000).

Figure 2 shows the frontogenesis terms and the average potential temperature gradient at 500 m MSL for a box following the front (cf. Fig. 1a). On this figure the frontogenesis evolution is also related to the average 500 m divergence within the box and the average model terrain height east of the box from the coast to the edge of the 3-km domain. As the front neared the coast between 0500 and 0900 UTC the CTL frontogenesis adjacent to the steep terrain increased rapidly from 0.5 to 4.5 K (100 km h)$^{-1}$ while the NCST frontogenesis only increased to 1.5 K (100 km h)$^{-1}$. During this period the deformation strengthened as a result of increasing convergence between the terrain enhanced flow and the front, as suggested by the differences between the CTL and NCST simulations. The enhanced convergence and associated precipitation along the front also resulted in diabatic frontogenesis dominating over the negative contributions from the tilting term. Between 0900 and 1100 UTC as the CTL front sagged south adjacent to lower topography and the coastal flow attenuated (not shown), the convergence and associated precipitation weakened. As a result, the total frontogenesis was less positive since the negative contributions from the tilting term dominated over diabatics and deformation frontogenesis no longer increased because of weaker convergent flow. Overall, these results support YS's hypothesis that decreased terrain blocking with the lower terrain to the south resulted in an attenuation of the NCFR.

Verification of the real-time MM5 forecasts at 36-, 12-, and 4-km resolution around Long Island has revealed some benefits and potential challenges of high resolution NWP near the coastal zone. For sea breeze events across southern New England the wind and temperature errors are reduced significantly from 36 to 12-km resolution (not shown), but there is little additional skill going to 4-km because of timing errors and near surface temperature biases. Verification of the MM5 warm season precipitation indicates an over-prediction problem just inland of the coast at 12-km resulting from an over-active Kain Fritsch convective scheme. Furthermore, the Kain-Fritcsh supresses the 4-km explicit precipitation, resulting in model biases less than 80% of observed. The convective scheme has been switched to Grell for the 36/12-km domains, which has resulted in a more realistic 4-km precipitation.

IMPACT/APPLICATION

Landfalling fronts and cyclones along the U.S. West Coast are often associated with strong winds, which are enhanced by the steep coastal topography ("barrier jet"), and heavy precipitation. This study has helped our understanding of landfalling fronts by diagnosing high resolution model simulations.

There has been limited objective verification of mesoscale models at high resolution along the coastal regions of the U.S. This study provides the first such verification along the southern New England coast down to 4-km resolution. This verification will help address the question whether increased computer resources should be spent towards running high resolution forecasts (< 10 km grid spacing) or a series of lower resolution ensemble forecasts to produce probabilistic predictions.

TRANSITIONS

The real-time MM5 forecasts and verification are sent to the surrounding National Weather Service forecast offices around New York City for the forecasters to evaluate and use on a daily basis.

RELATED PROJECTS

1 – Our East Coast real-time MM5 and verification effort is a natural extension of Cliff Mass' real-time MM5 over the West Coast which is also sponsored by ONR.

SUMMARY

Landfalling frontal temperature gradients and associated precipitation intensify not only by flow blocking near coastal terrain, but also from latent heating and cooling within the frontal cloud and changes in the flow aloft. During the next year we will systematically identify how these effects change as the large scale atmospheric conditions are systematically altered within an atmospheric model.

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